Mixing Sludges & Slurries with Pulsed Jets: Some mixing theory & Test Results

Slurry Retrieval, Pipeline Transport & Plugging & Mixing Workshop
January 14 - 18, 2008, Orlando, Florida.

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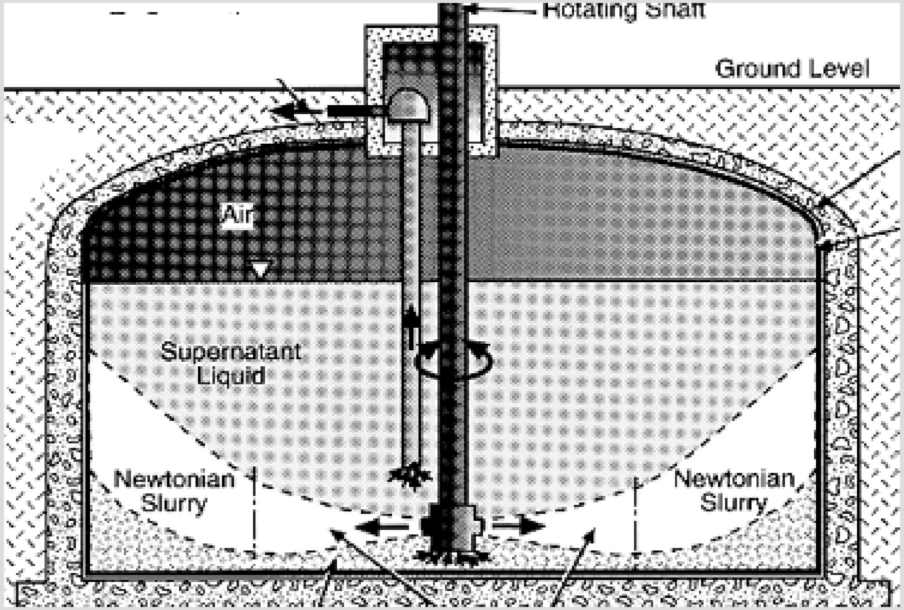
Unsteady Jet Mixers at Hanford

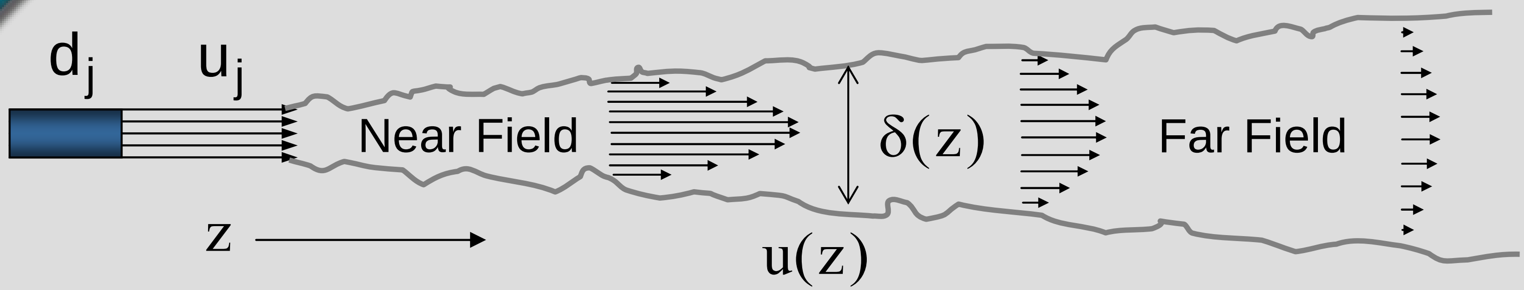
- Retrieving from storage
  - Underground, 1 - 2ft risers
  - Limited access for equipment
  - 2 - 300hp mixer pumps (baseline)
- Treating & vitrifying waste
  - Closed “black” cells
  - No maintenance for 40 years



Rotating horizontal opposed jets

Pneumatic pulsed jets

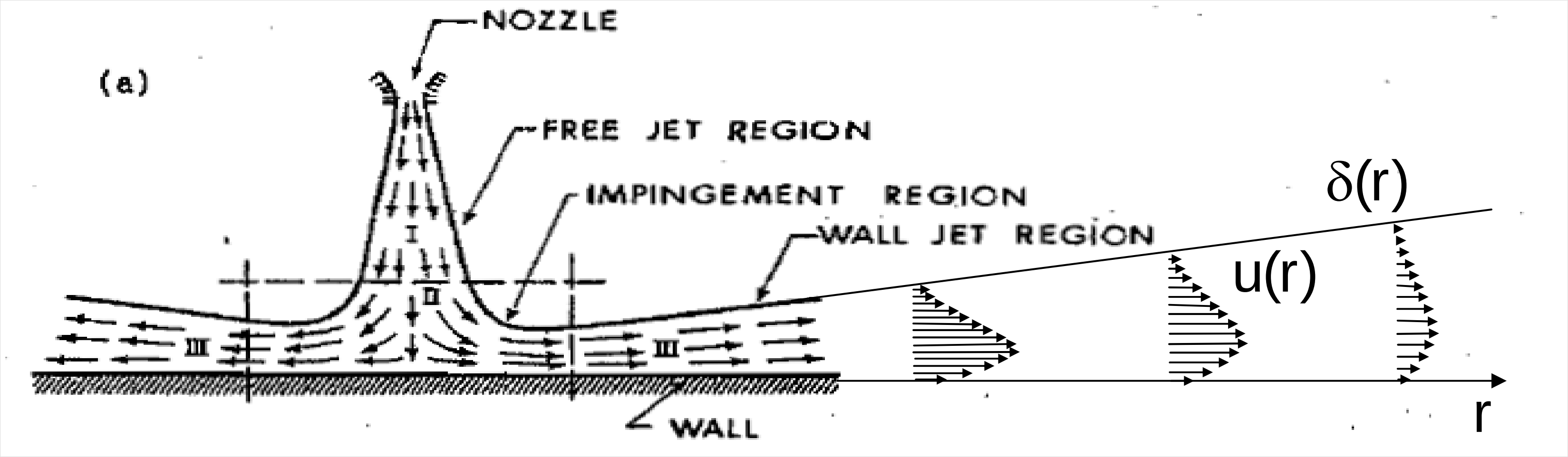
Turbulent Jets



- High Reynolds number far field
  - Constant spread angle $\delta(z) = \theta z$
  - Peak & ave. velocity decrease $u(z) = c_j u_j d_j / z$ $u_d A$
  - Thrust/force is constant $F(z) = F_j$
  - Flow rate increases (entrainment) $q(z)/q_j \sim z/d$
  - Energy decreases $e(z)/e_j = d/z$
  - Constant Reynolds number $Re_\delta(z) = Re_d$

Turbulent Jets, cont.

- Same results for impinging & attaching jets
  - Different constants
  - Wall shear stress $\tau_w(r) \sim \rho u_j^2 (d_j / r)^2$
- True independent of nozzle cross-sectional area
- Approximately true in near-far-field transition $z / d_j,\ r / d_j = 15 - 30$
- Allows one to approximately obtain flow fields, fluxes, forces, etc
- Similar relations for dense jets

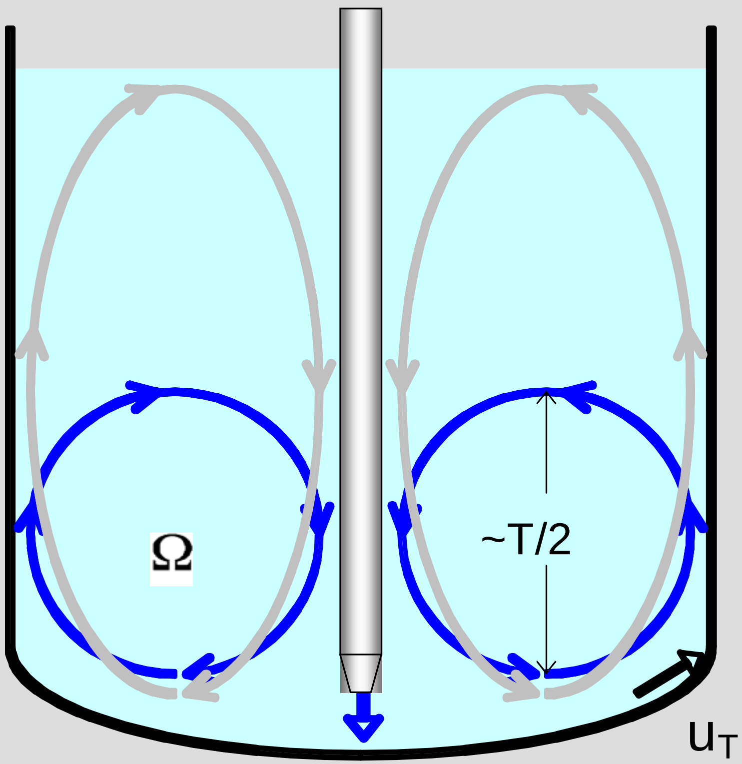


Jets as mixers

- Axial flow impeller: ND ~ uj
  - dj/T <<1 (careful about blindly applying agitator results)
  - Power, thrust, and flow numbers = ~ 1
    - Much higher power than agitators for same thrust
    - Lower flow, higher head
- Highly directional
  - point them where you want them
  - Must design for thrust reaction
- Return placement
  - Can be important

Downward vertical jet mixers

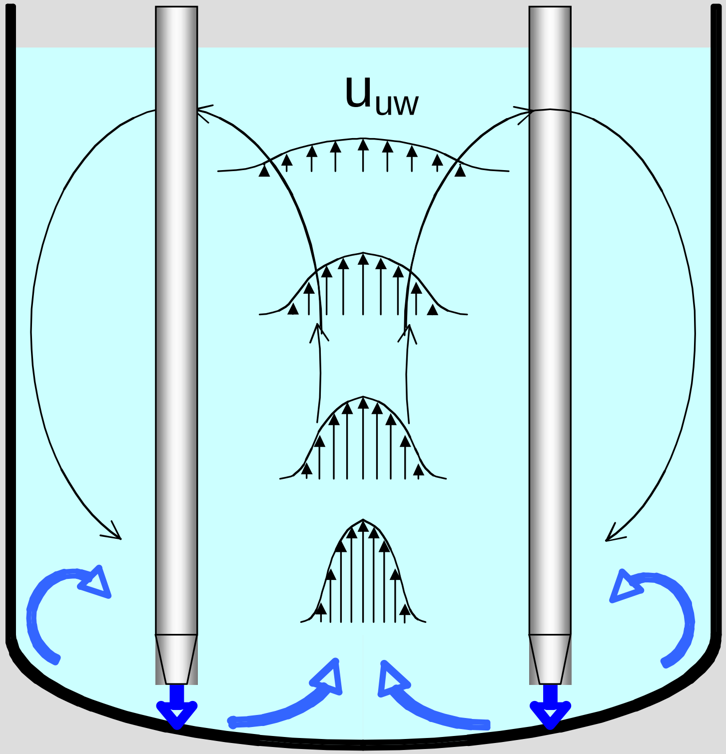
Centered Jet(s)



$$u_T \sim u_j (d_j / T)$$

$$\Omega \sim u_j d_j / T^2$$

Jet rings(s)



$$u_{uw} \sim u_j \sqrt{N_j} (d_j / T) \times f(H/T)$$

$$t_{uw} \sim T^2 / u_j d_j \sqrt{N_j} \times f^2(H/T)$$

Geometry

- Nozzle geometry
  - Cross-section: No effect in far field- only area counts
  - Convergence: extra thrust from pressure
- Stand-off
  - No effect for $h/dj < 6$, little effect for $h/T<<1$
- Number of jets
  - $N^{1/2}dj$ momentum/thrust effect
  - $T/N^{1/2}$ ZOI geometric effect
- Return location
  - Can be important- Avoid short-circuiting
- Dish shape
  - Impingement angle- flow distribution
- Other internals
  - Wakes/blockages

Intermittent Jets

- Dimensionless pulse time determines regime

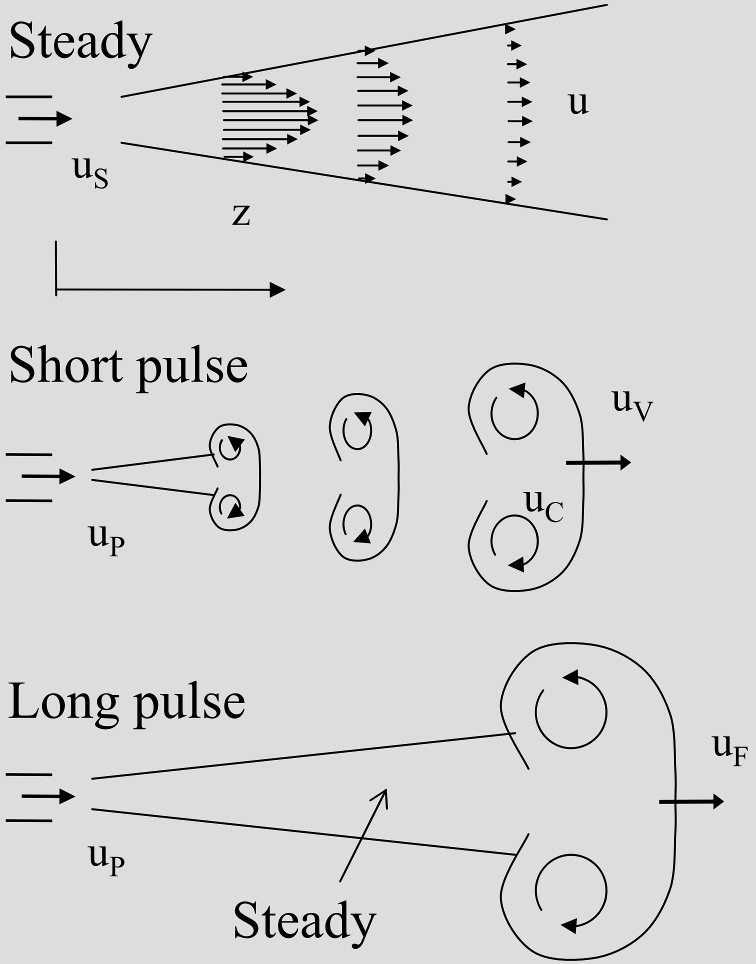
$$N_p = t_p u_d / d$$

$N_P < 4$ vortex ring

$4 < N_P$ vortex ring with tail

$4 << N_P$ developing steady

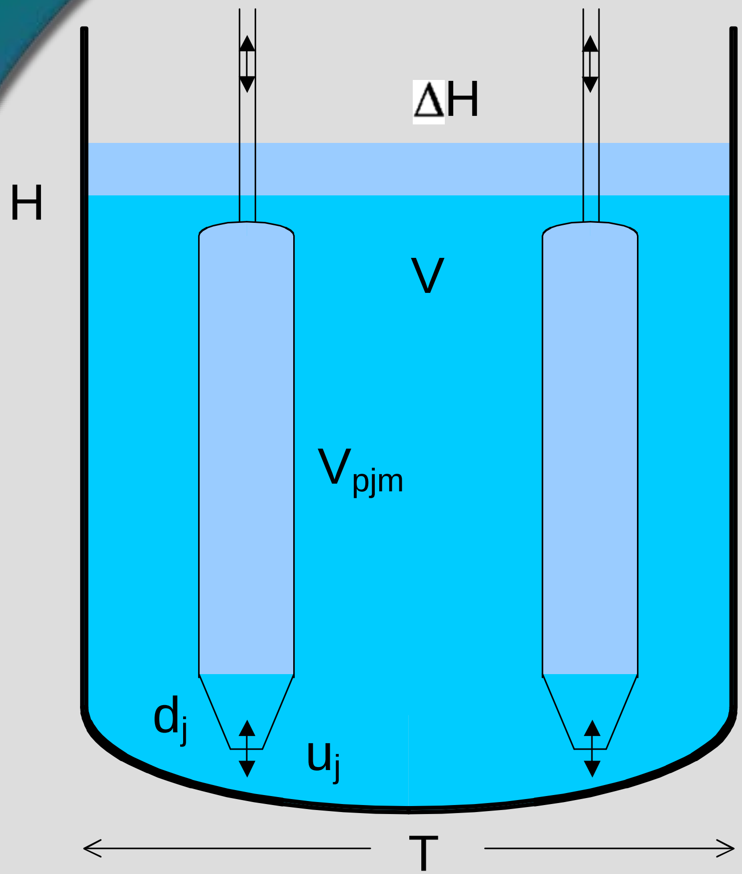
PJMs: N_P = 80 - 500

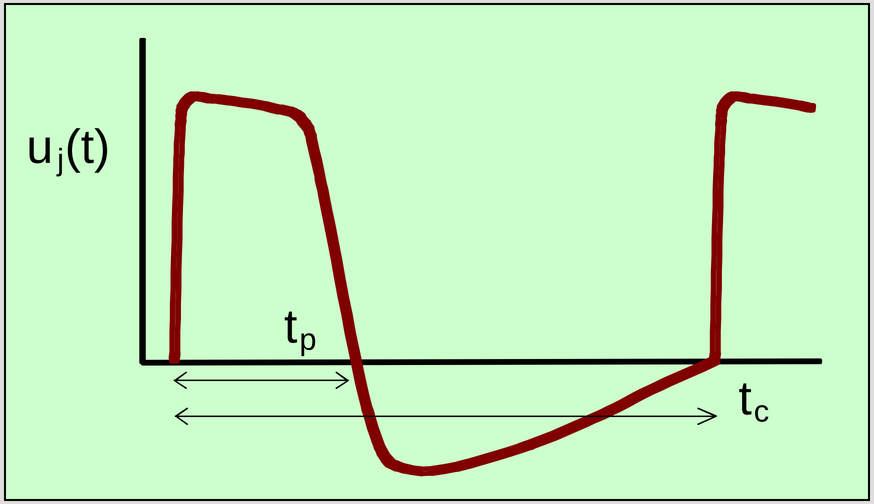


Unsteady effects on mixing/mobilization

- Would like to utilize steady mixing knowledge base
  - Can we find simple corrections for unsteady effects or are we dealing with fundamentally new phenomena?
- Must consider relative time scales
  - Flow establishment/mixing times compared with pulse time
  - Duty cycle
    - What happens when the jet is off?
  - Other time scales
    - Erosion rates
    - Settling rates
    - Etc.
- Two new parameters are introduced
  - Relative pulse volume
  - Duty cycle

Pulse jet mixers





- **Mixing modes**
  - drive
  - refill

- **PJMs in the WTP**
  - V (range)
  - N (range)
  - Pvf (range)
  - DC (range)
  - Dpjm (range)

Important parameters

- Geometry

N	number jets
Uj	jet velocity (peak)
d_j/T	nozzle diam.
$\Phi_p = V_p/V$	pulse size
$DC = t_p/t_c$	duty cycle
geometry	

- Operational

- Waste physical configuration
  - Normal/off-normal operations
  - Uniform
  - Settled layers

- Physical & rheological properties

Pulse Jet Mixing Studies at Battelle/PNNL

- Physical regimes
  - Transitional flow
  - unsteady
  - Non-settling/non-Newtonian
  - Settling- wide particle size & density range, agglomerates
  - Heels- cohesive/non-cohesive
  - In situ gas generation
- Mixing requirements
  - Stagnation/caverns
  - Off-bottom suspension- V_{JS}
  - Vertical distribution
  - Gas hold-up & release behavior
- Scaled testing program
  - Simulant development
    - Physical/chemical
    - Transparent/opaque
    - 1/2/3 phase
  - Testing
    - Bench scale - 40m^3
    - Single & multi jets
    - simplified & prototypic geometries
  - Scale up
    - Rating, not designing
    - Similarity, physical, empirical
  - Instrumentation

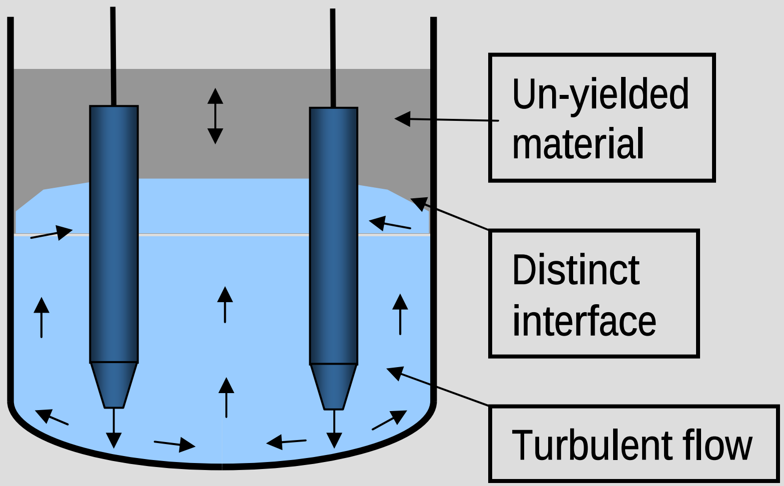
Non-Newtonian PJM Test Program

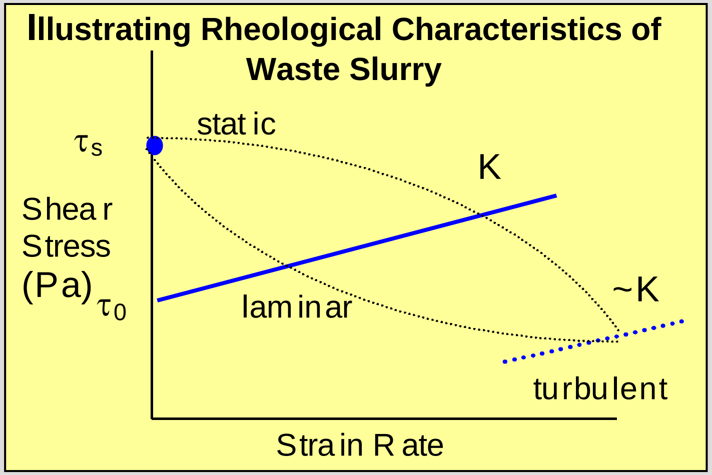
- Technical basis
  - Develop scaled testing approach
  - Validate approach- limited testing at scales
- Rate existing designs
  - (3 unique designs in WTP)
- Improved PJM designs
- PJM/sparge hybrid designs

Theory of PJM Operation with Non-Newtonian Materials

- Model problem: Cavern formation
  - Initially gelled material
  - Representative of restart after mixing shutdown
  - Good mixing system will eliminate cavern
- Rheological model
  - Static gel formation with shear strength τ_s
  - Bingham plastic laminar flow rheology with yield stress τ_0 and consistency K
  - Turbulent flow characteristics determined by high shear consistency ~K

Typical Pulse Jet Mixer System





Cavern Formation from a Steady Jet

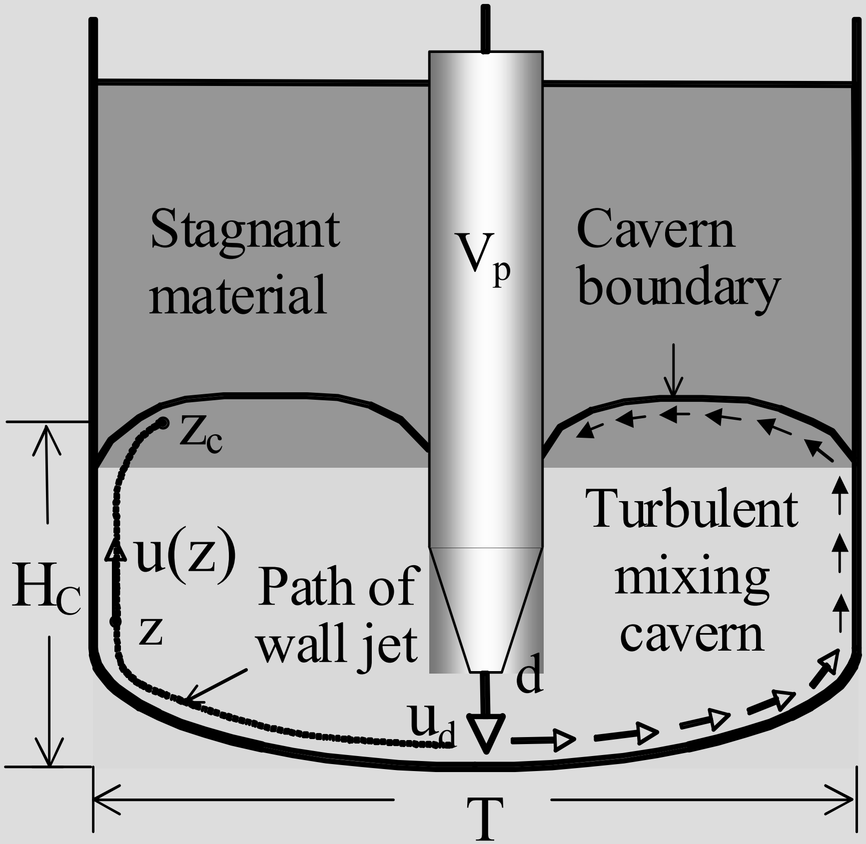
- Turbulent wall jet

$$u(z) = c_J u_d d / z \qquad \tau_f = C_f \rho u^2 / 2$$

- Force balance at static interface

at $z_C \approx H_C + T/2 \qquad \tau_f = \tau_s$

$$\boxed{H_C / T = a(d/T) Re_\tau^{1/2} - 1/2}$$



- Yield Reynolds Number

$$\boxed{Re_\tau = \rho u_d^2 / \tau_s}$$

- Reynolds number dependence

$$Re_d = \rho u_d d / k \qquad C_f\ ,\ c_J = f(Re_d)$$

$$\boxed{a \sim Re_d^{-\beta}}$$

Theory of PJM Operation in Non-Newtonian Materials

- Cavern Formation from a Steady Jet
  - Turbulent jet theory with force balance at interface predicts cavern height
- Yield Reynolds number
  - Ratio fluid force to material strength

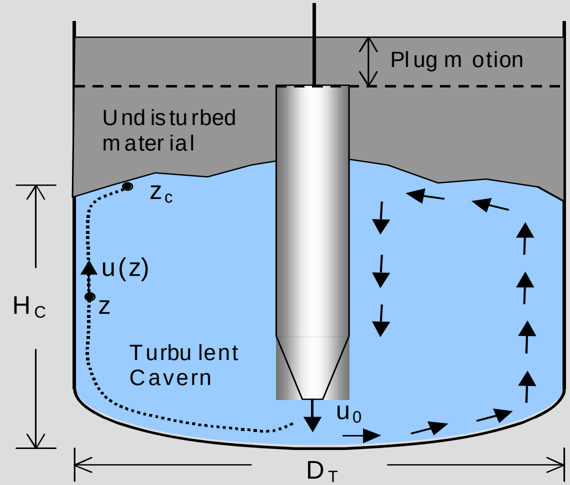
$$Re_\tau = \rho u_0^2 / \tau_s$$

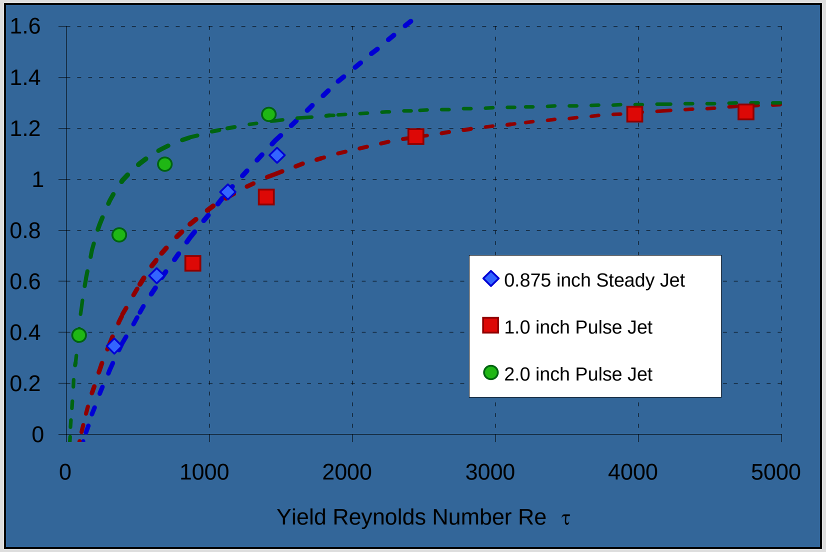
- Effects of pulsation
  - Ratio PJM drive time to flow establishment time

$$t_D / t_{ss} \sim V_p / d_0^3 Re_\tau$$

- Predicted cavern height

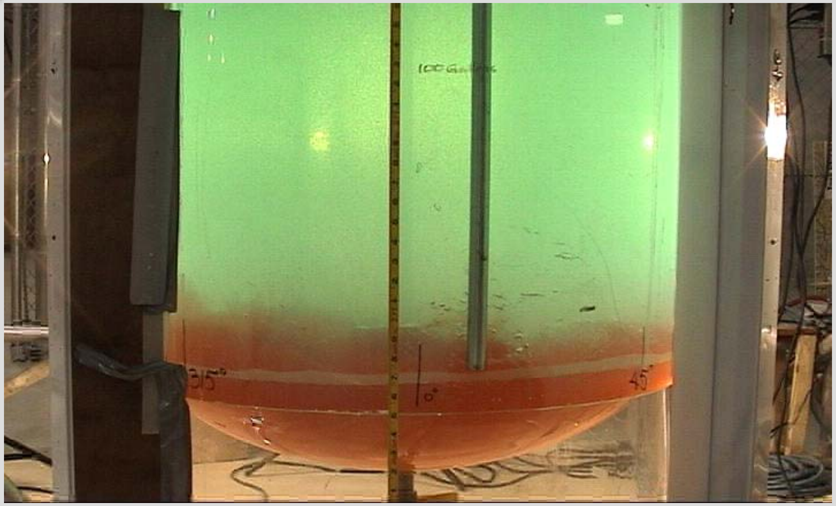
$$\frac{H_c}{D_T} = a \frac{d_0}{D_T} Re_\tau^{1/2} \left(1 - \exp(-c \frac{V_p}{d_0^3 Re_\tau})\right)^{1/2} - \frac{1}{2}$$

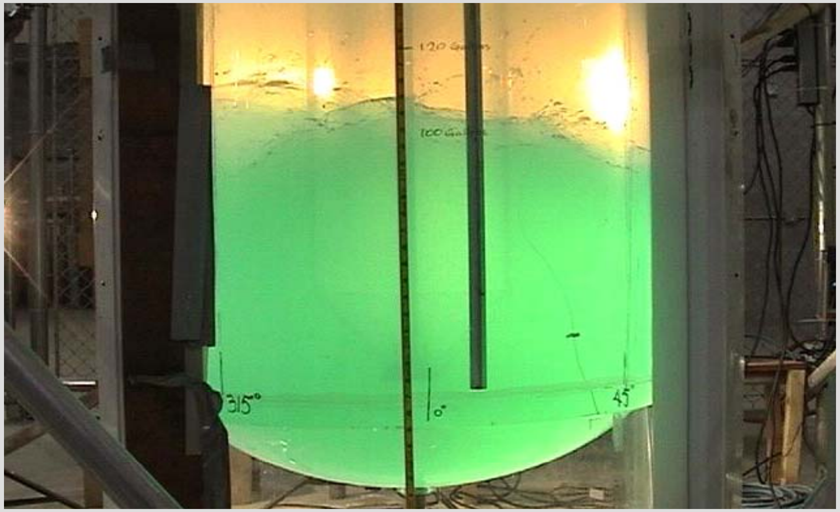


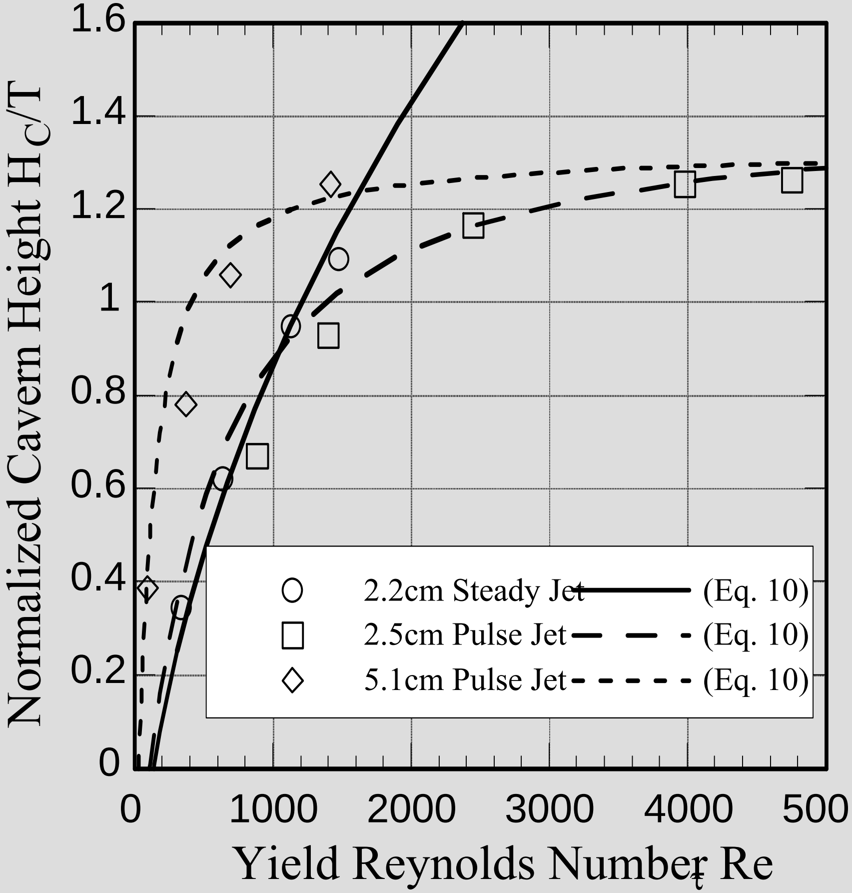


Non-dimensional cavern height as a function of yield Reynolds number for a single PJM in Laponite

Single-PJM Cavern Tests (laponite)

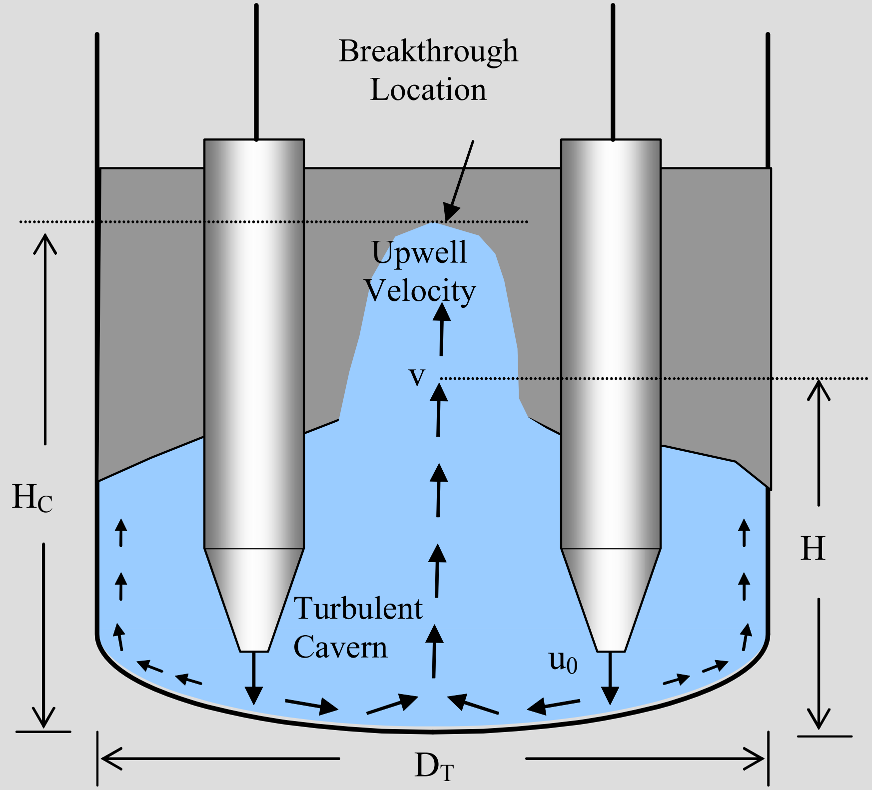






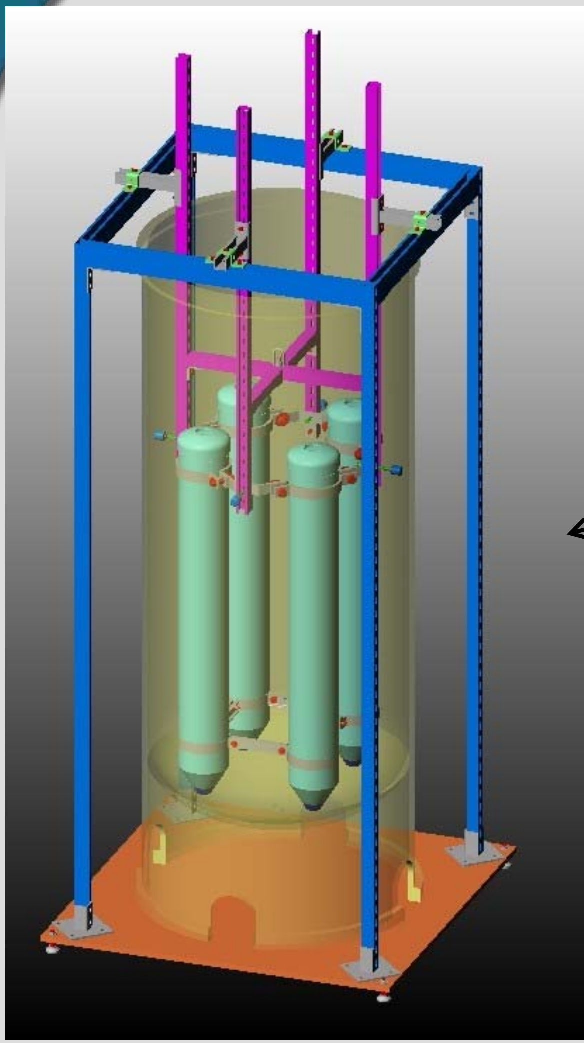
Test to Verify Scaled Testing Approach

- **1PJM Tests**
  - Simulant selection
  - Verify cavern formation theory
- **4PJM Tests**
  - Downward firing PJMs
  - Performed at 3 scales
- **Simulants**
  - Laponite
    - Transparent
    - Adjustable shear strength
  - Kaolin/Bentonite Clay
    - Opaque
    - Adjustable yield stress/consistency
- **Test conditions**
    - Rheology (20 -120 Pa)
    - Velocity (3-30 m/s)



- **Types of measurements**
  - Cavern height (Laponite)
  - Breakthrough velocity (clay & Laponite)
  - Upwell velocity (clay)

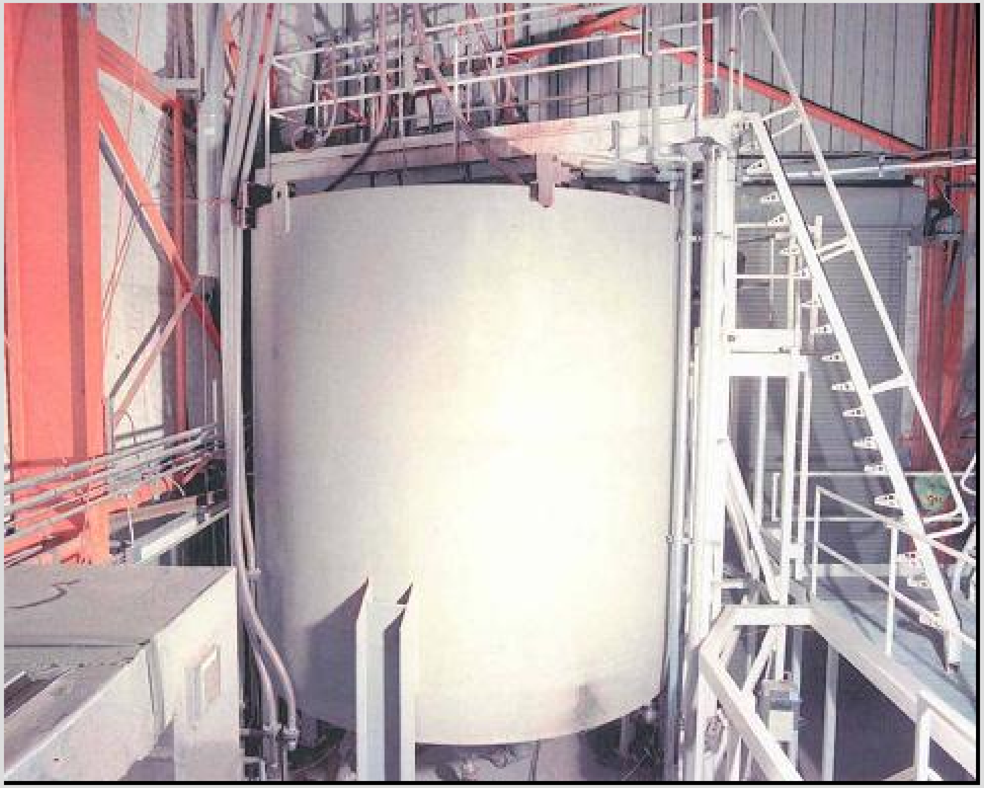
Small Scale Test Stands



- Battelle 1/4-scale 4 PJM Test Vessel
  - 34 in. diameter
  - 250 gallons
  - Acrylic vessel
  - Compressed air/vacuum PJM drive system
- SRNL 1/9-scale 4 PJM Test Vessel
  - 17 in. diameter
  - ~30 gallons
  - Acrylic vessel
  - Compressed air/vacuum PJM drive system

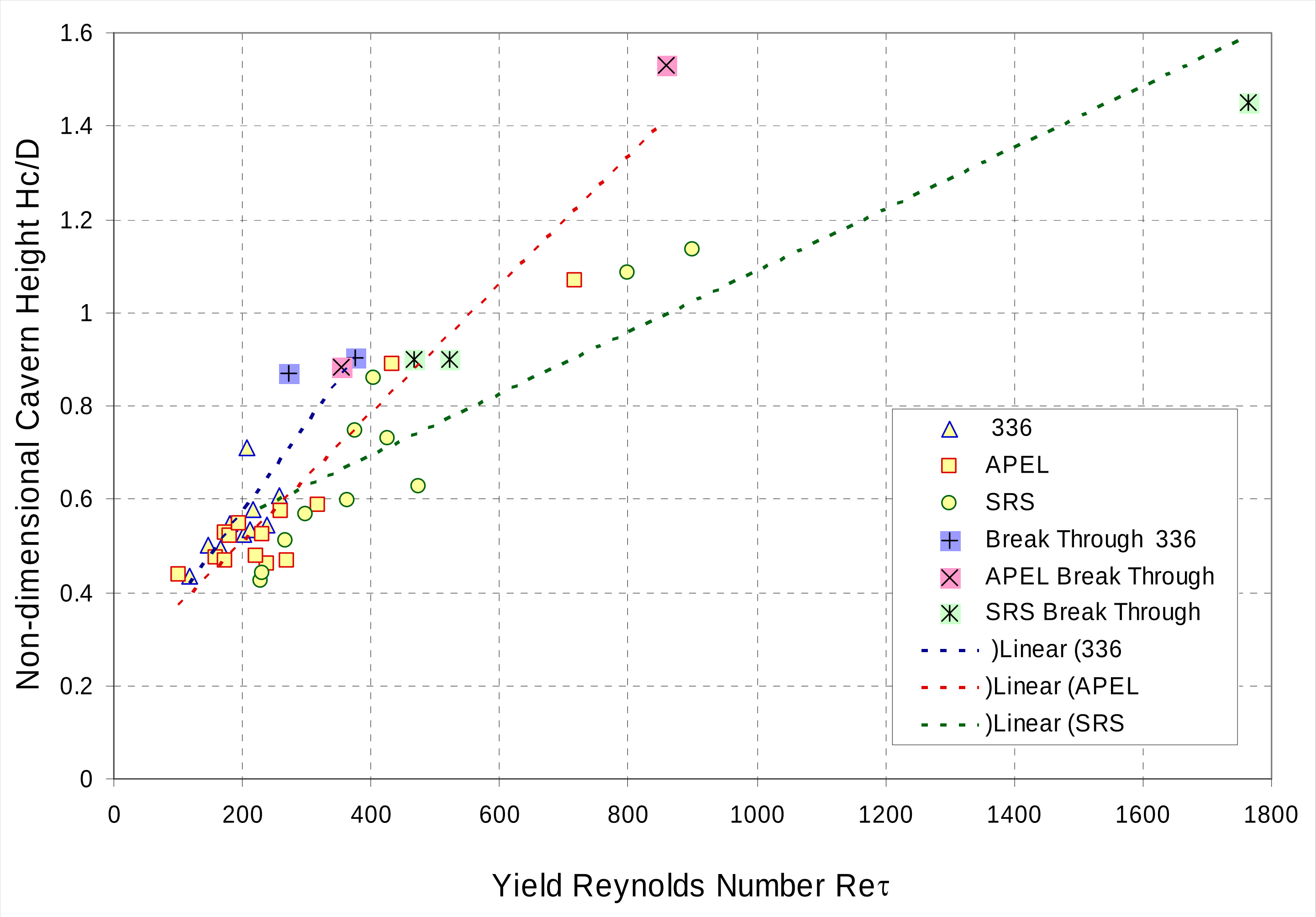
Large-Scale Test Stand at Battelle

- Battelle 336 4 PJM Test Vessel
  - ~13 ft. diameter, ~12,000 gallons
  - Steel construction
  - Prototypic AEA Compressed air PJM drive system



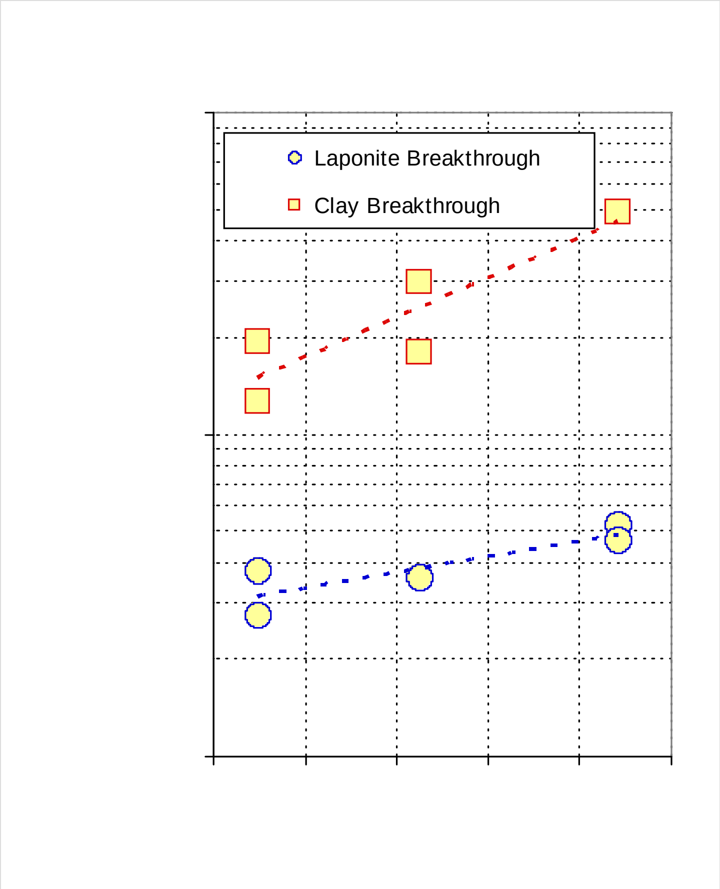
- Pulse tube prior to installation
  - 24 in. diameter
  - 2 in. conical nozzle

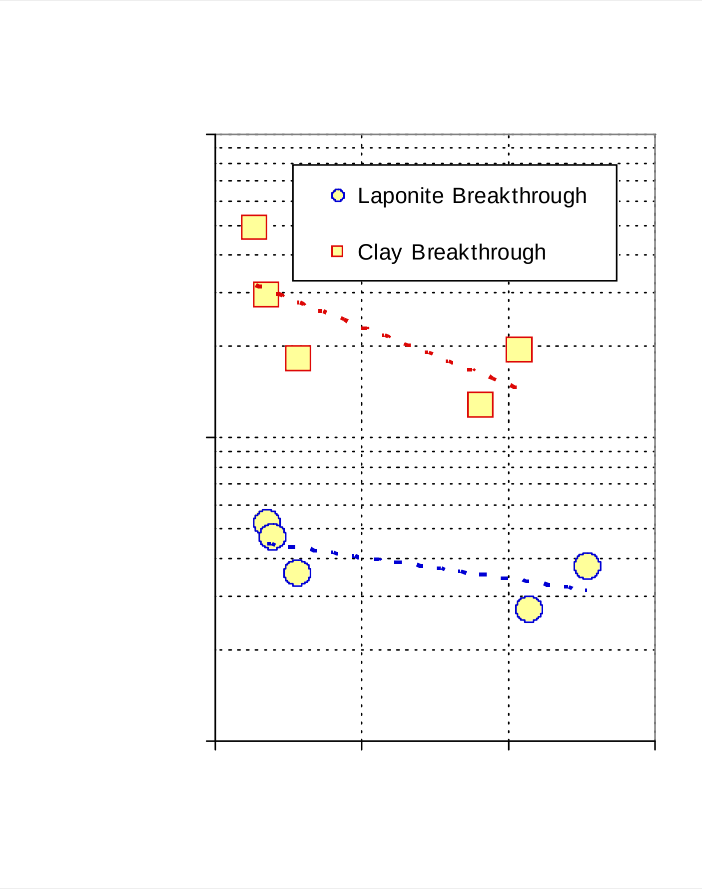
Scaling Data Comparisons



Comparison of cavern position for tanks of 3 different scales with Laponite simulant.

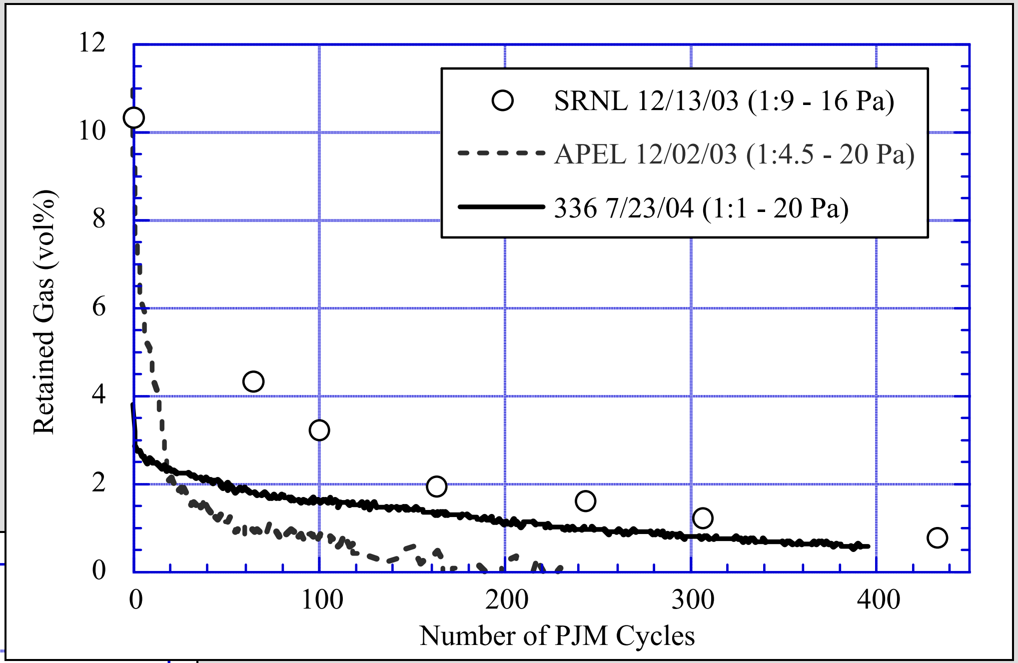
Scaling Data Comparisons

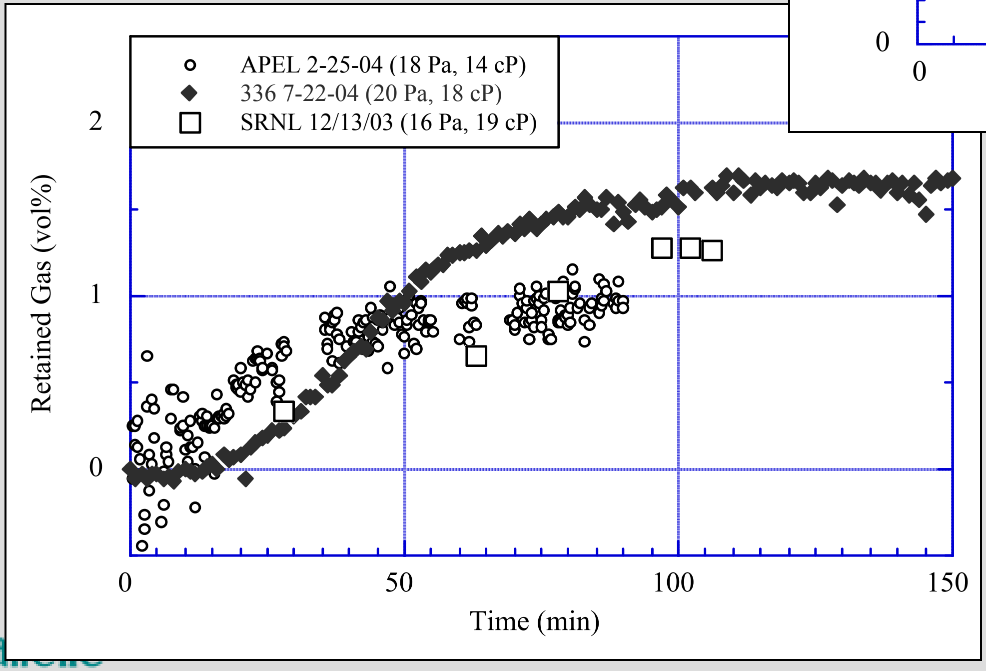




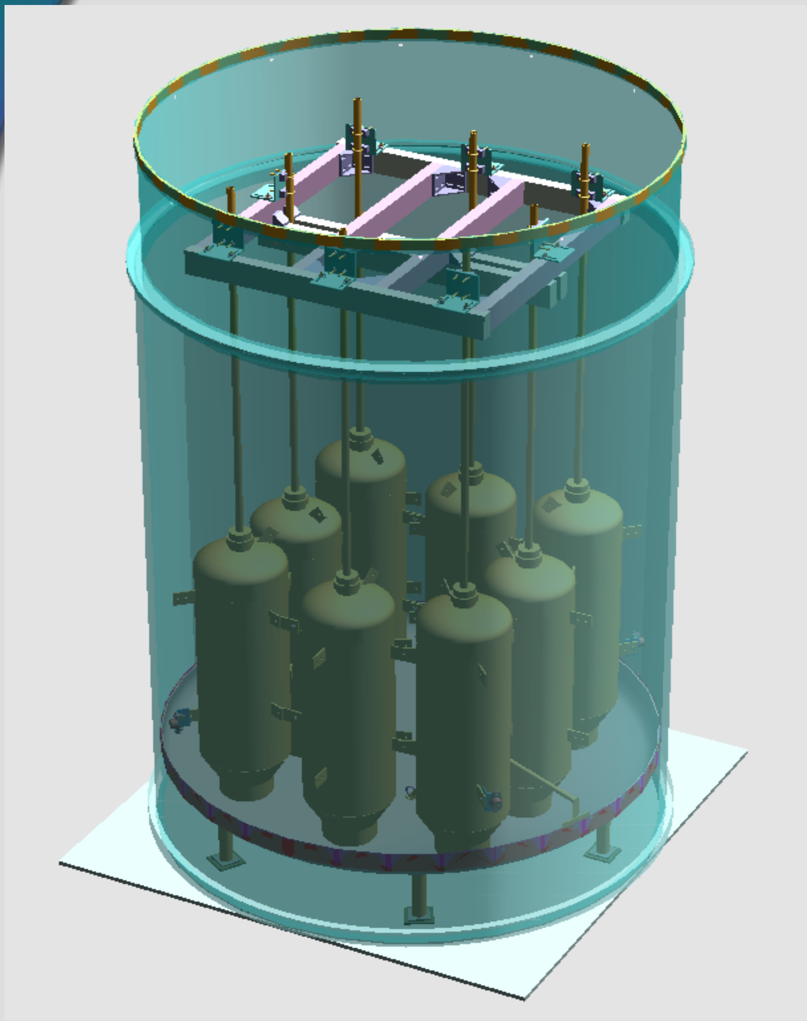
Comparison of surface breakthrough velocity for tanks of 3 different scales with Laponite & clay simulants.

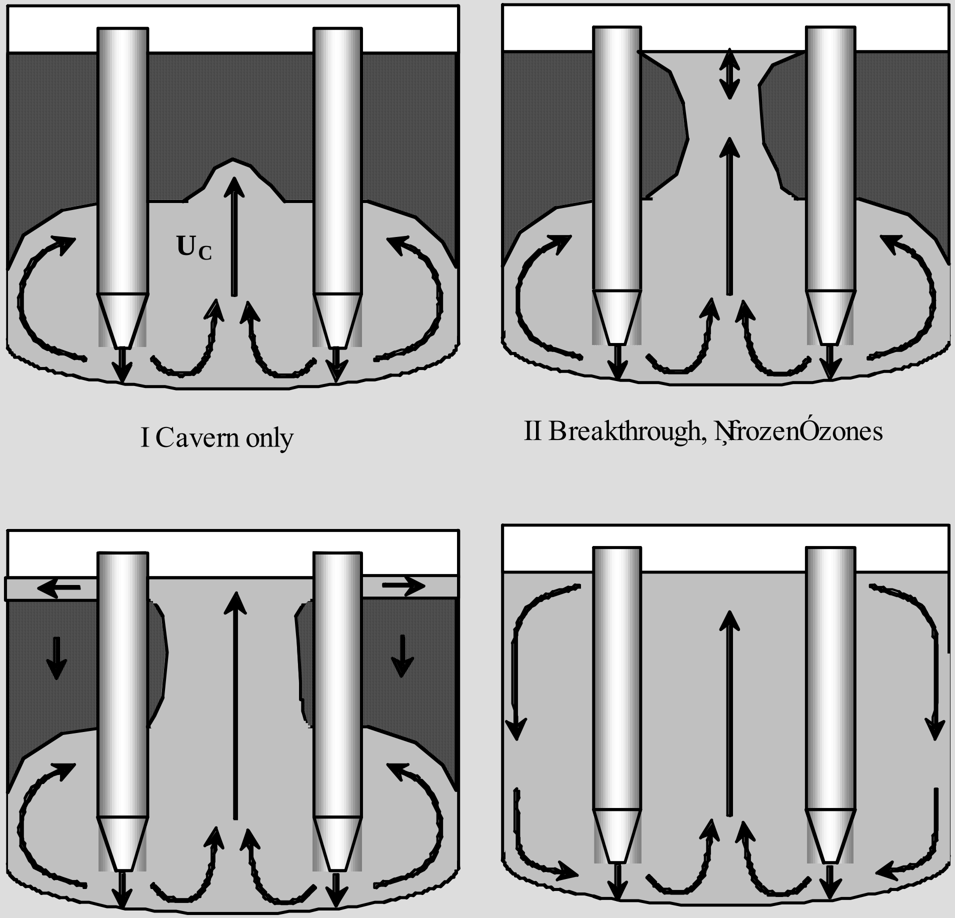
Gas hold-up & release- tests at 3 scales





Baseline Designs





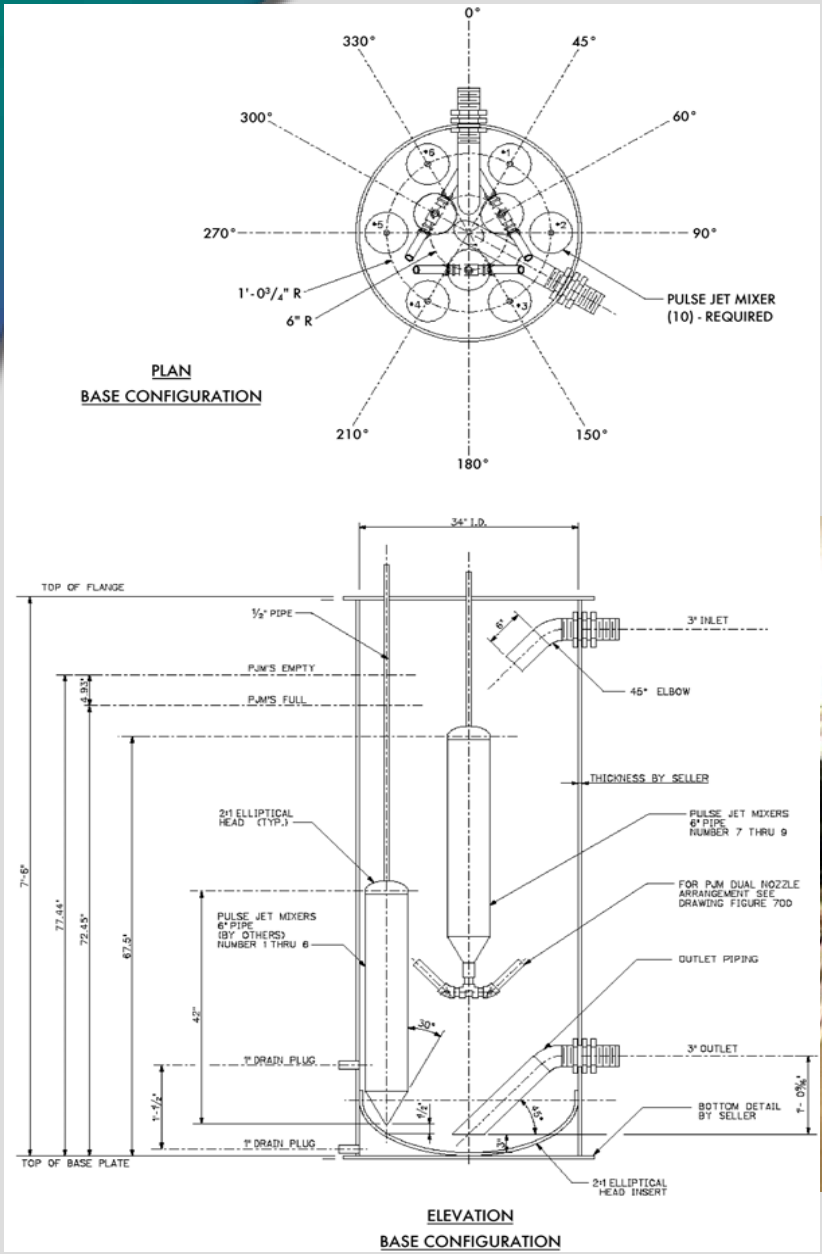
I Cavern only

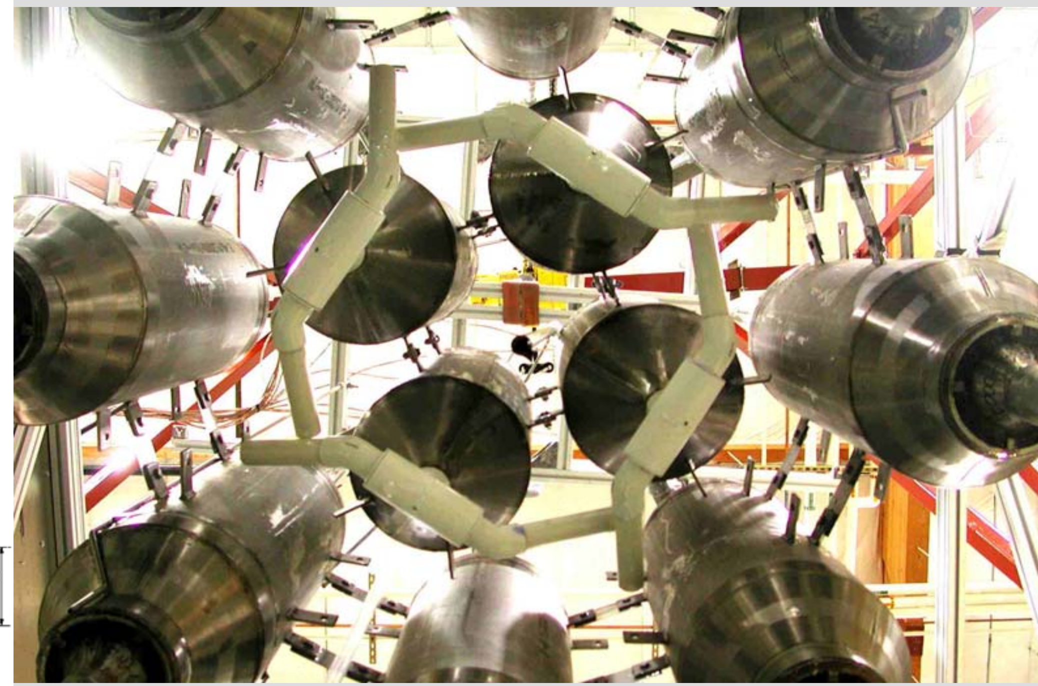
II Breakthrough, ŅfrozenÓzones

III Breakthrough with slow peripheral movement

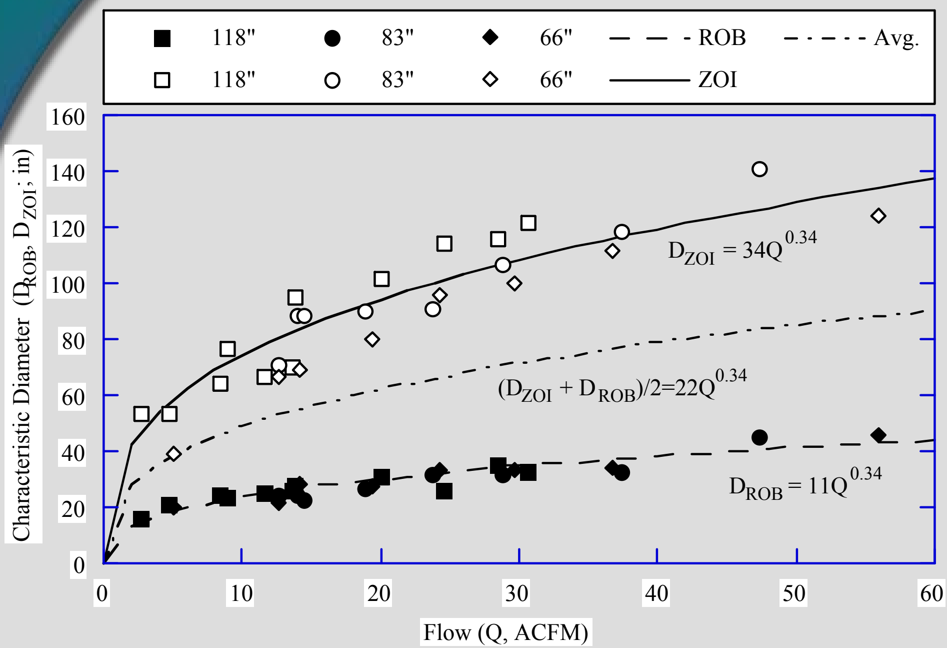
IV Full turbulent mixing

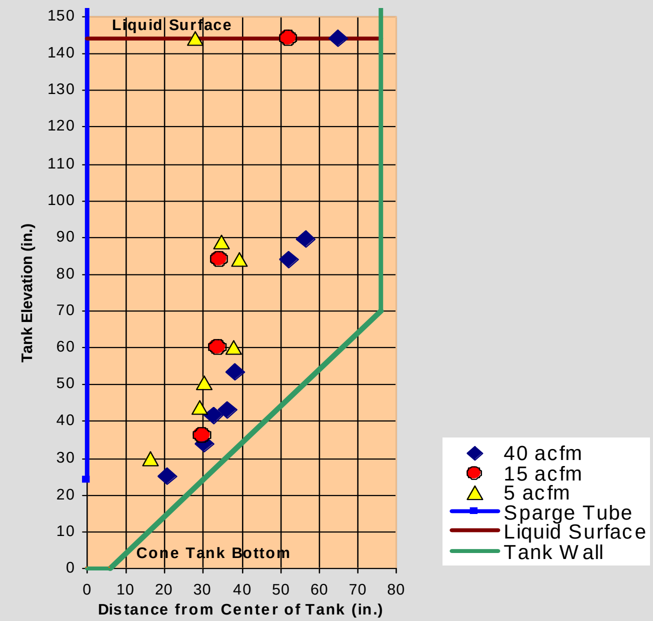
Improved PJM designs

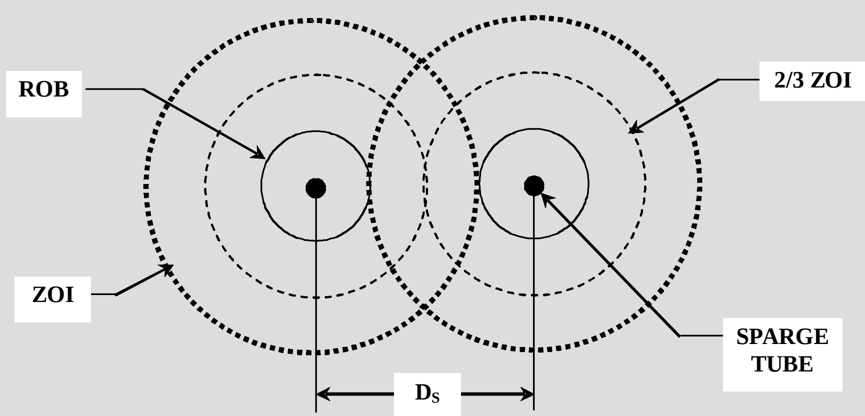


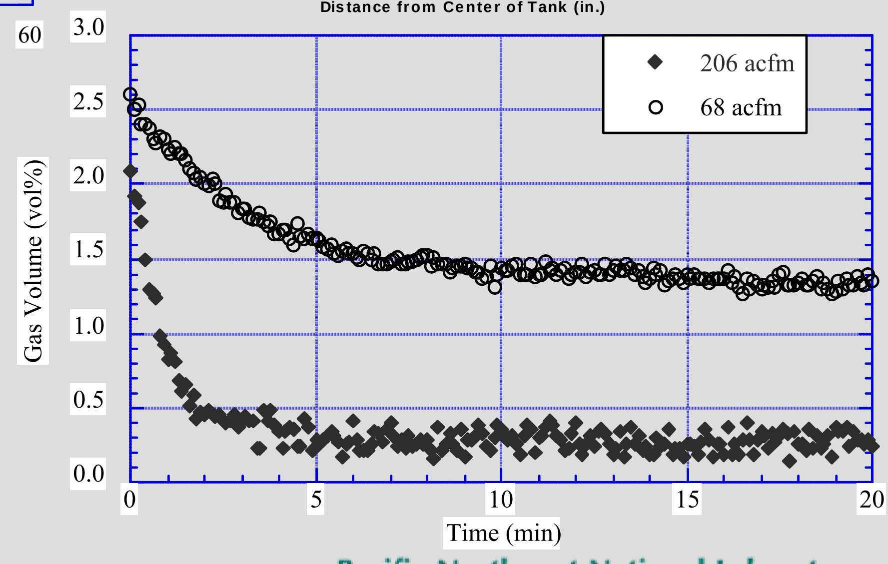


Air sparging in Bingham Plastic Slurry

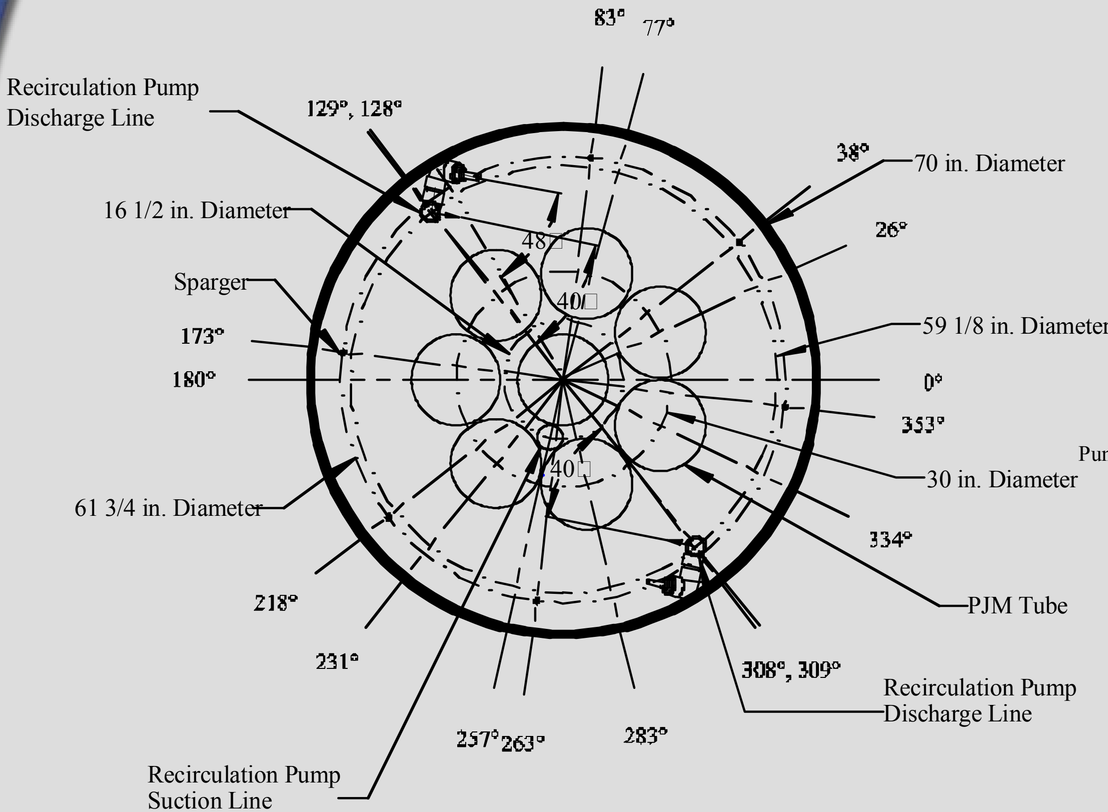


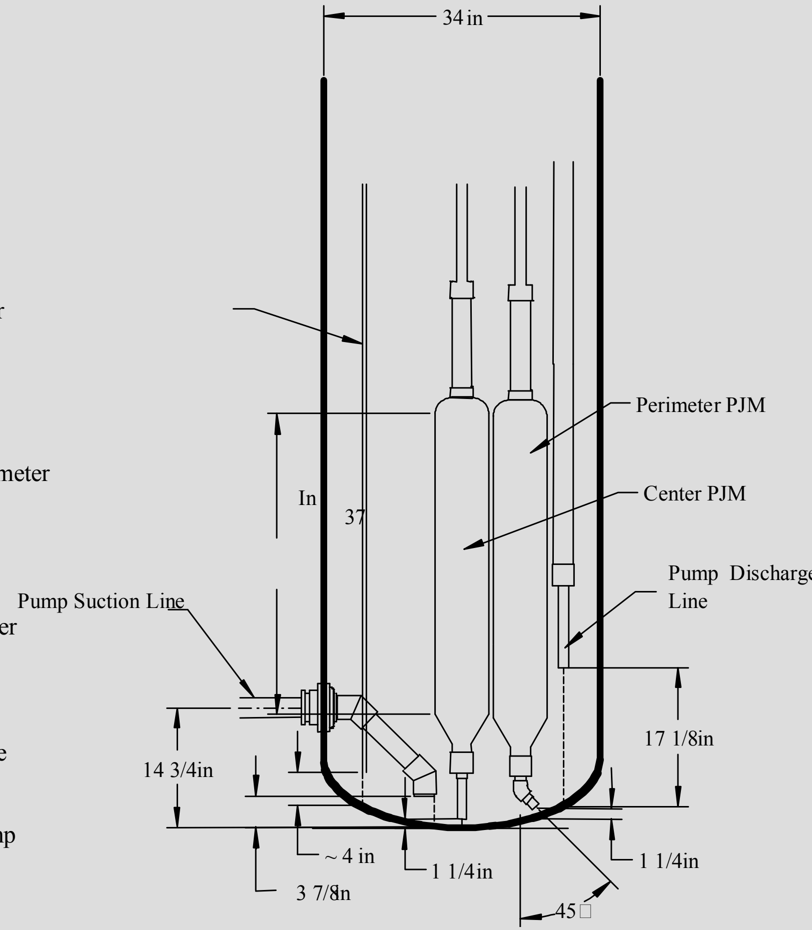




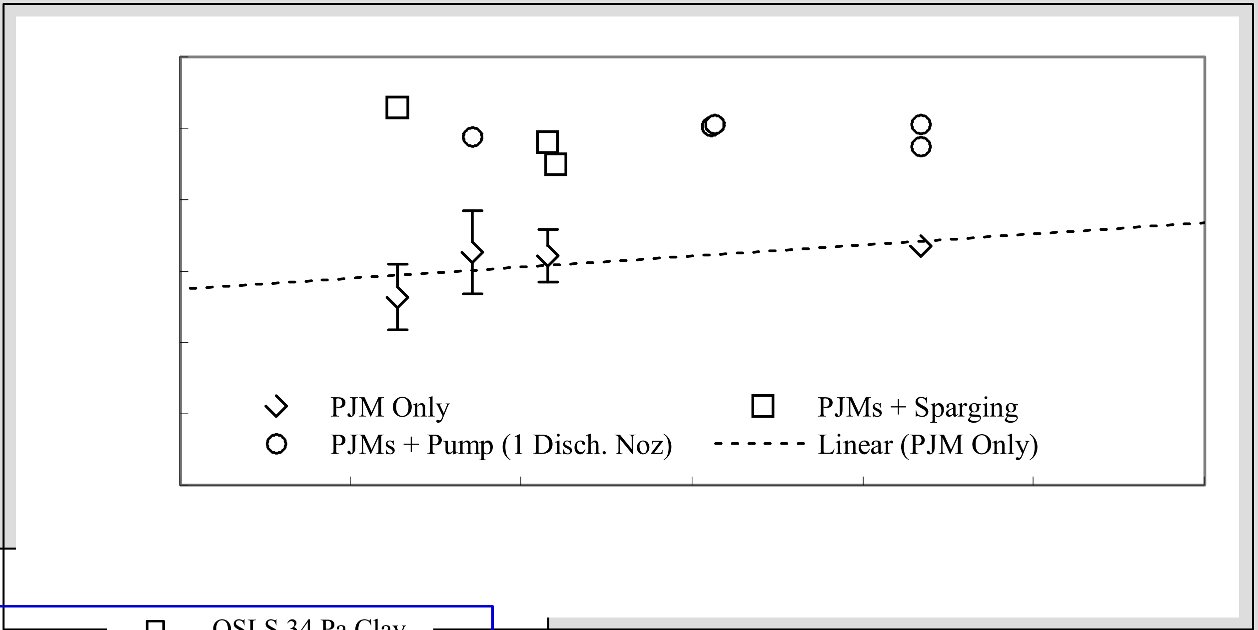


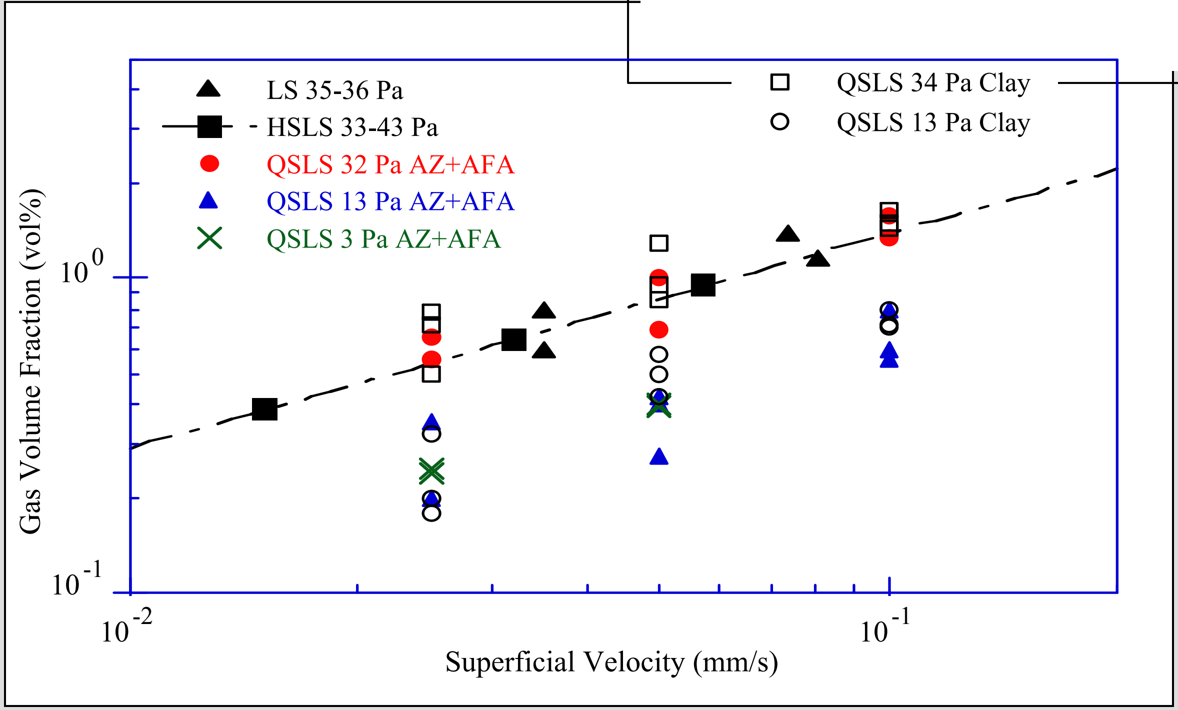
PJM/air-sparge hybrid designs





Final Design Mixing Performance





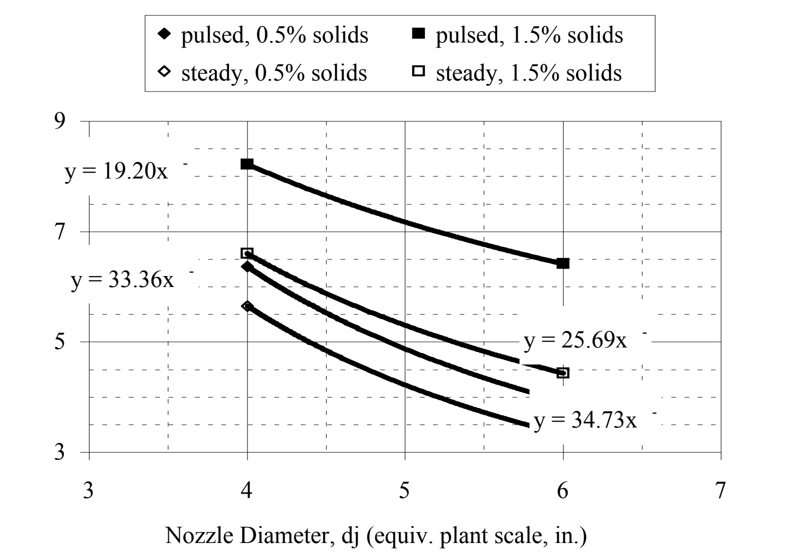
M3- Rating WTP Mixing Systems

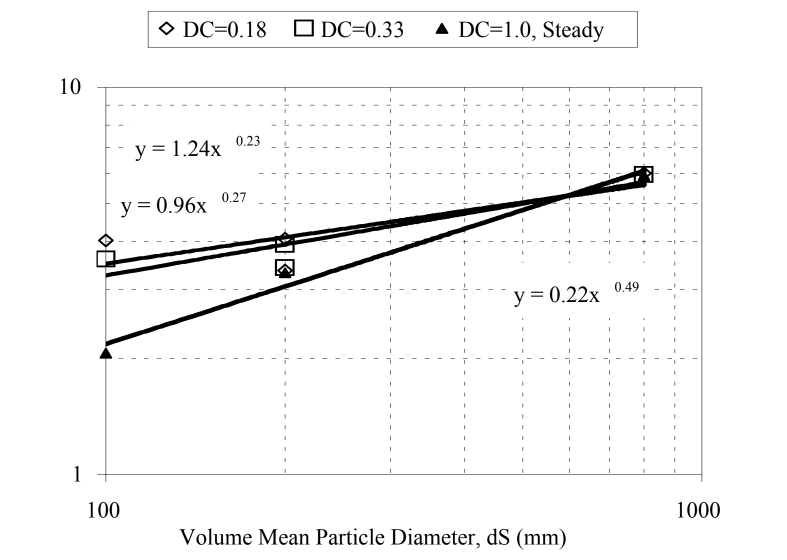
- Rate mixing system designs for balance of WTP vessels
  - Normal operations & mixing restart
- Broad range of potential waste conditions
  - Non-cohesive (settling) solids - cohesive solids
  - Wide range of solids size, density, slurry rheology
- 18 different vessel/mixing system geometries
- Primary metrics
  - Off-bottom suspension
  - Vertical solids distribution
  - Blend times
- Work in 3 phases: non-cohesive, cohesive, gas handling

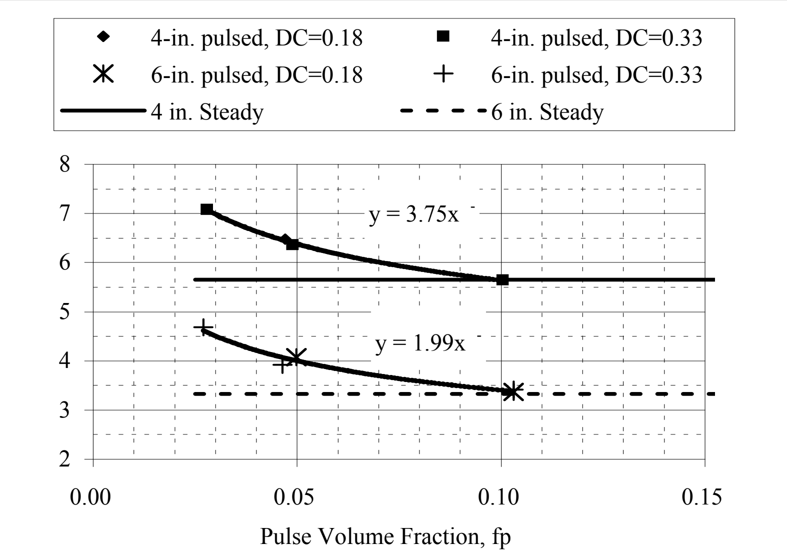
Preliminary tests with non-cohesive solids

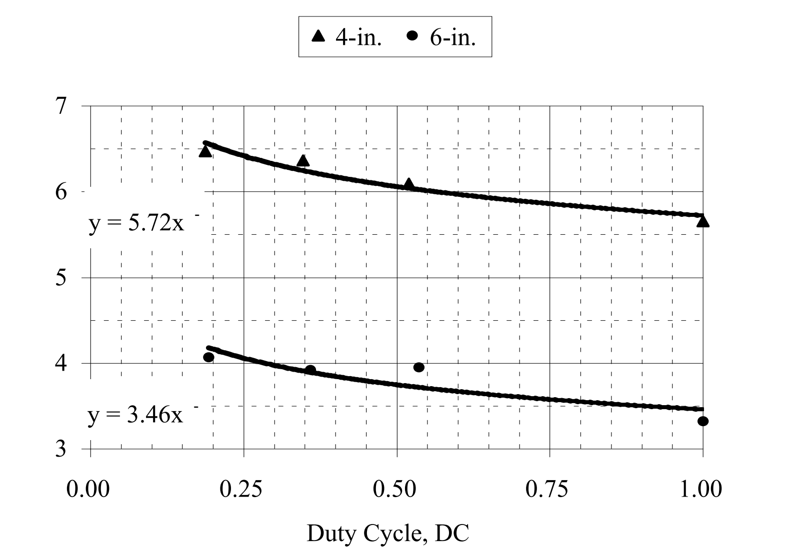
- Simulants
  - Glass spheres (low grade), S ~ 2.47
  - 3 sizes: d_s = 63-100, 150-210, 600-800μm
  - 2 solids loadings: ϕ_s = 0.005 & 0.015
- Vessel geometries
  - 34-in., 1/13.4-scale of HLP-22
  - 12 tubes, 0.3 & 0.45-in nozzles (4 & 6-in. full scale)
- Operational
  - Pulse volume fraction ϕ_p = 0.025 - 0.10
  - Duty cycle: DC = 0.18, 0.36, 0.5, 1 (steady)
- Measurements
  - Ujs & peak cloud height

Some off-bottom suspension results









Correlating just-suspended velocity

- Assume Zwietering values for un-tested parameters

$$\mathrm{Ucs} = k(H/D')^{0.14} g^{0.5} (s-1)^{0.43} (D')^{1.3}$$

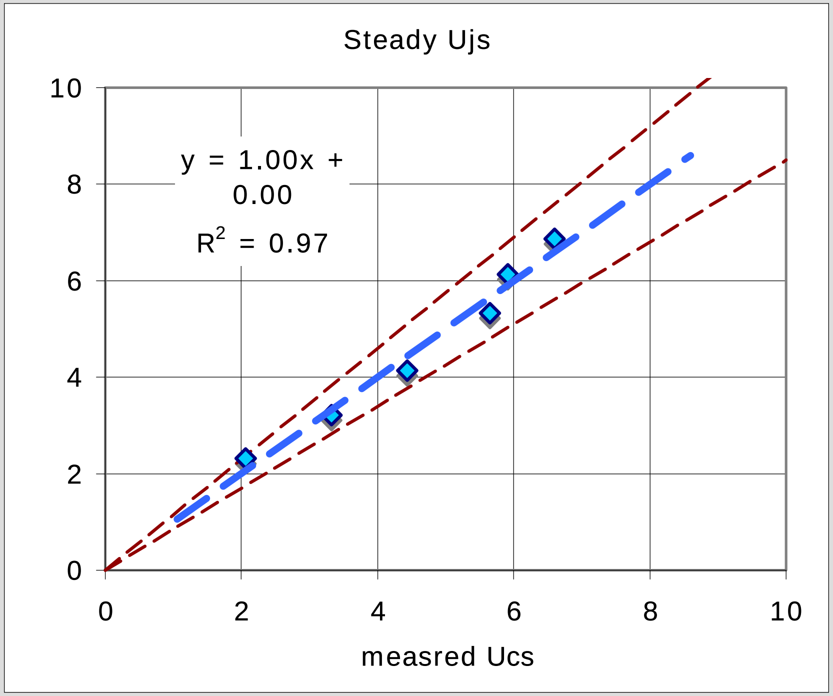
$$\times \quad (d_s)^{a_5} (d_j)^{a_6} (100 s\phi_s)^{a_7} (DC)^{a_8} (\phi_p/(1+\phi_p))^{a_9}$$

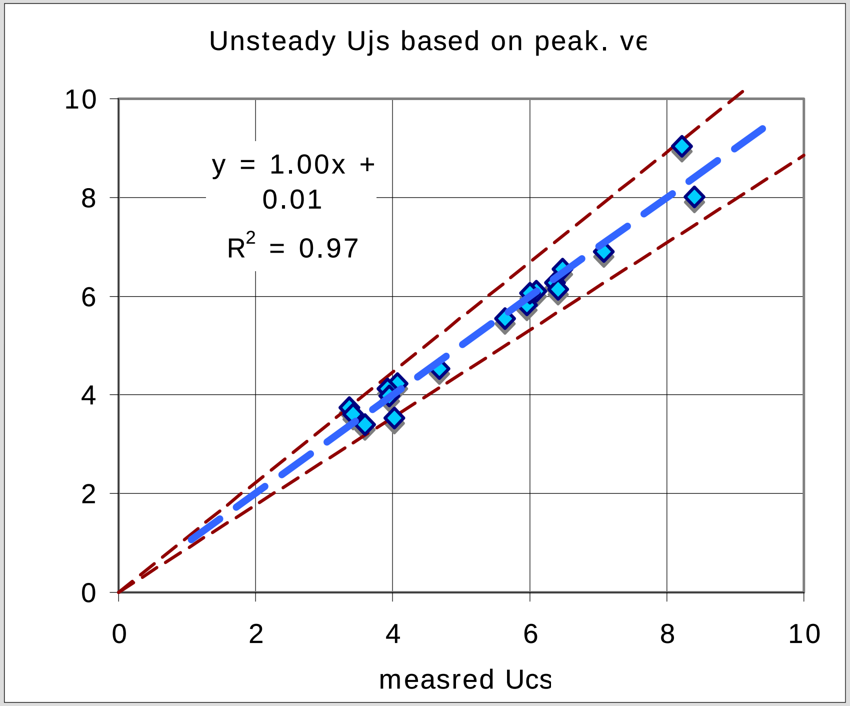
$$D' = D/\sqrt{N}$$

	Steady	Pulsed
k	0.78	0.23
d_s	0.47	0.26
d_j	-1.3	-1.06
$S\phi_s$	0.23	0.34
DC	-	-0.06
ϕ_p	-	-0.18

Preliminary data for information only

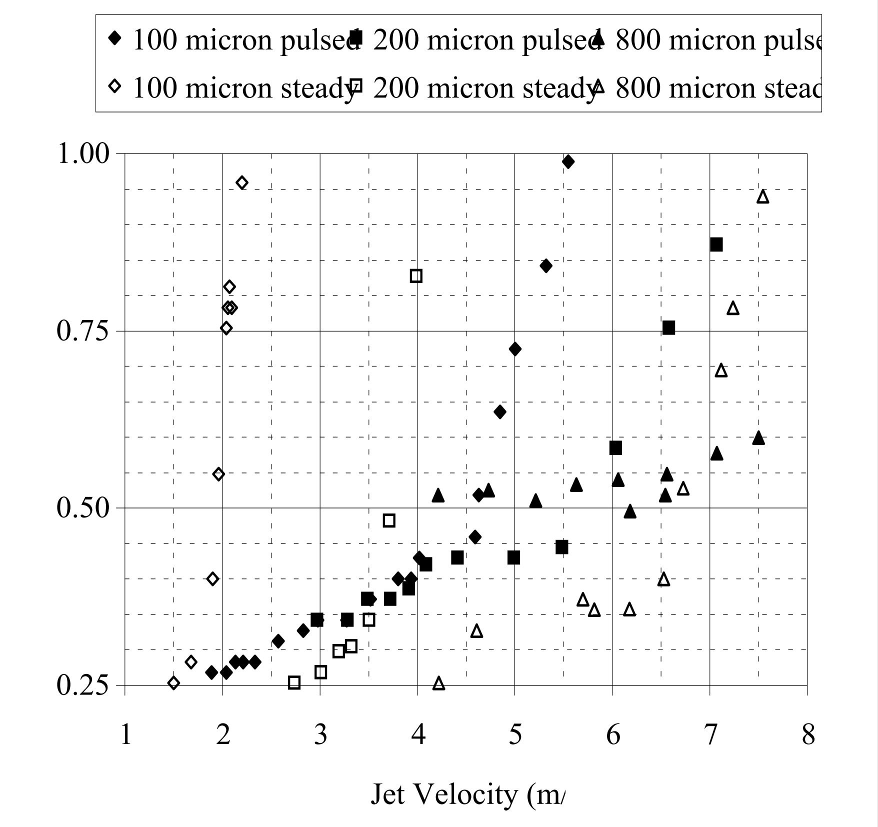
Data correlation: off-bottom suspension

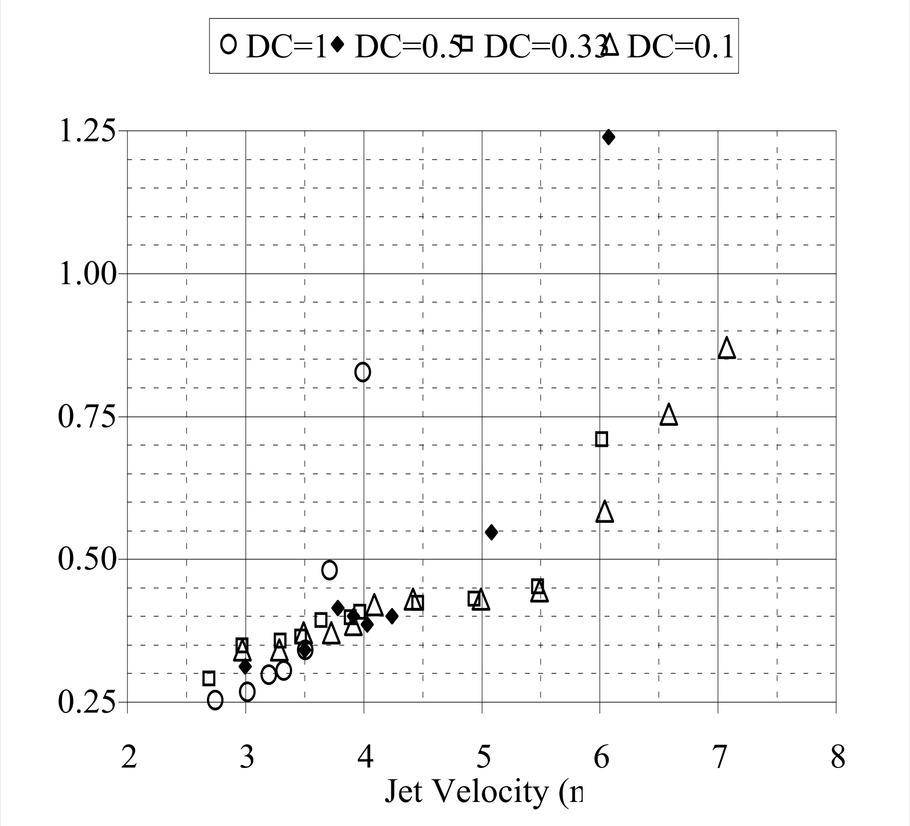




- Suggests pulsation effects small at low concentration
- Scale-up to plant conditions: design likely inadequate
  - More testing at additional scales & higher solids required

Cloud height data





Preliminary data for information only

Correlating cloud-height

- Simple energy argument
  - Energy per pulse ~ change in potential energy of solids

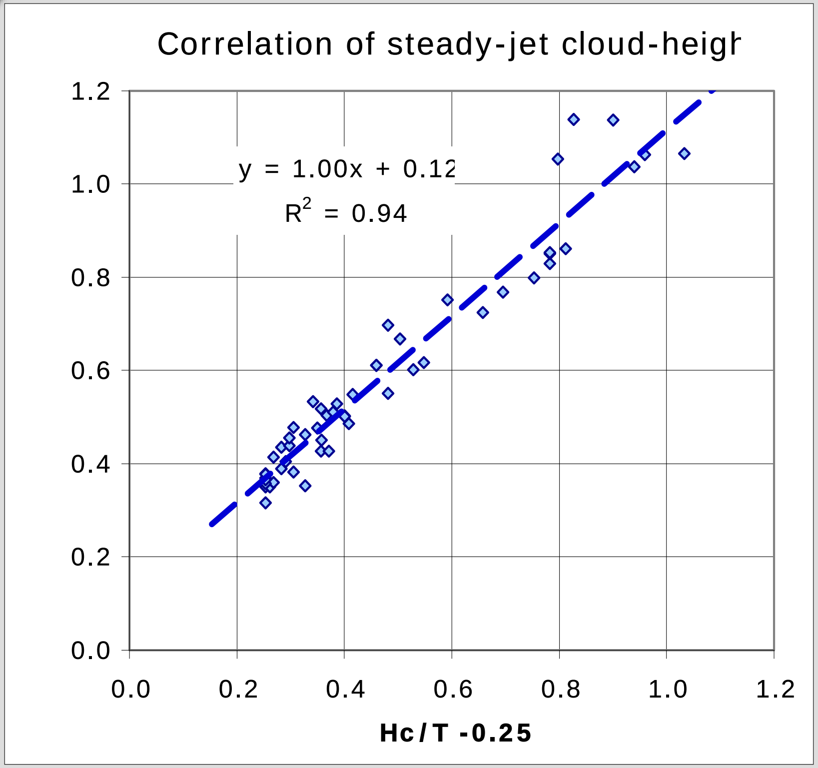
$$\phi_p F_H \sim \frac{\phi_s}{\phi_d} \qquad F_H = \frac{u^2}{2(s-1)gH_c}$$

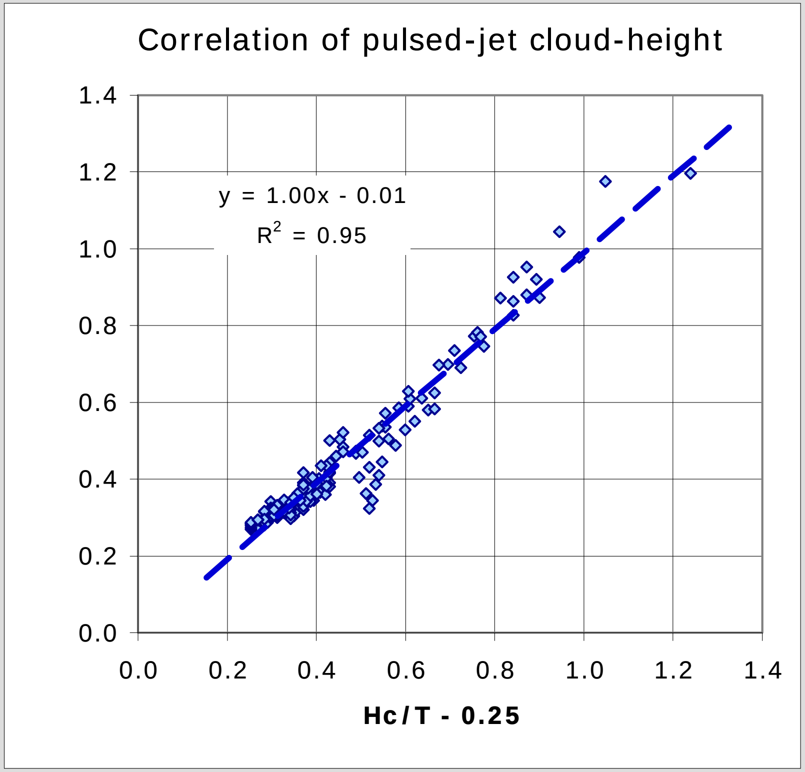
$$\frac{H_C}{D} \sim F_D \frac{\phi_p \phi_d}{\phi_s} \qquad F_D = \frac{u^2}{2(s-1)gD}$$

- Attempt correlation of the form

$$\frac{H_C}{D} \sim F_D{}^{a1} \phi_p{}^{a2} \phi_d{}^{a3} \phi_s{}^{a4} \qquad \text{include} \quad d_s/D \quad \text{or} \quad u_s/u$$

Correlation of cloud-height data





	k	U	ϕ_s	ϕ_d	d_s/T	ϕ_p	DC
Steady	2.8	2	-0.56	1.7	-1.1	-	-
Pulsed	7.1	2	-1.1	1.0	-0.5	0.3	0.25

Preliminary data for information only

Summary of findings

- Just suspended velocity
  - Unsteady effects minor
    - DC effects negligible
    - There is evidence this breaks down at higher concentration where time to suspend > drive time
  - Similar solids size effect
  - Concentration exponent 2x
  - Effect of nozzle size as expected
  - To be sure, need more data

Summary, cont.

- Vertical distribution
  - Strong bulk density stratification effect
  - Unsteady effects appear to dominate
    - Exponents on DC & PVF
    - Fundamental behavior
  - Weak solids size dependence:
    - Define U_{JH} ("just to H…"). Then $U_{CH} \sim d_s^{0.25}$
  - Strong concentration effect: $U_{CH} \sim \phi_s^{0.5}$
  - Strong pulsation effect: $U_{CH} \sim \phi_p^{-0.5}$